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The AIRES system for air shower simulations. An update.

S. J. Sciutto$^{(a)}$

Departamento de Física, Universidad Nacional de La Plata, Argentina

Abstract. A report on the characteristics of ultra-high energy air showers simulated with the current version of the AIRES program is presented. The AIRES system includes a fast simulating program, originally designed on the basis of the well-known MOCCA program, and progressively improved and tested. The AIRES algorithms are briefly described and some results coming from the simulations are analyzed.

1 Introduction

When an ultra high energy astroparticle interacts with an atom of the Earth's atmosphere, it produces a shower of secondary particles that continue interacting and generating more secondary particles that can eventually hit the Earth's surface. The study of the characteristics of such air showers initiated by ultra high energy cosmic rays is of central importance. This is due to the fact that presently such primary particles cannot be detected directly; instead, they must be studied from different measurements of the air showers they produce.

Due to the complexity of the processes that take place during the development of an air shower, detailed studies of its characteristics are commonly made with the help of numerical simulations. The simulating algorithms must take into account all the processes that significantly affect the behavior of the shower. This includes electrodynamic interactions, hadronic collisions, photonuclear processes, particle decays, scattering, etc.

Among all those processes, the hadronic and photonuclear reactions are, at present, the less understood. In the case of air showers initiated by ultra-high energy astroparticles ($E \geq 10^{19}$ eV), the primary particles have energies that are several orders of magnitude larger than the maximum energies attainable in experimental colliders. This means that the models used to rule the behavior of such energetic particles must necessarily make extrapolations from the data available at much lower energies, and there is still no definitive agreement about what is the most convenient model to accept among the several available ones. On the other hand, the results obtained for the most common shower observables prove to have a non negligible dependence with the model used to simulate the low energy hadronic collisions (with energy less than a few hundred GeV). Despite the fact that both high and low energy hadronic collision models are tuned using experimental data (energies less than $\approx$ 100 GeV), their predictions in the transition region do not agree completely, being this an undesirable characteristic of such models that is still not completely understood.

The **AIRES system**[1] (Sciutto, 1999) is a set of programs to simulate air showers. One of the basic objectives considered during the development of the software is that of designing the program modularly, in order to make it easier to switch among the different models that are available, without having to get attached to a particular one. The MOCCA code created by A. M. Hillas (Hillas, 1997) –successfully used to interpret experimental data coming from the Haverah Park experiment– has been extensively used as the primary reference when developing the first version of AIRES (Sciutto, 1997), launched four years ago.

Later releases have progressively incorporated new developments, including a complete revision, correction and extension of all the physical algorithms.

AIRES has been successfully used to study several characteristics of the showers, including comparison between hadronic models at the highest energies (Anchordoqui et. al., 1999), influence of the LPM effect (Cillis et. al., 1999), muon bremsstrahlung (Cillis and Sciutto, 2001), and geomagnetic deflections (Cillis and Sciutto, 2000). It has also been employed to study the expected efficiency of the Auger Observatory for detecting quasi-horizontal showers generated by τ neutrinos (Bertou et. al., 2001), and to calibrate a reconstruction technique for analyzing quasi-horizontal show-

Correspondence to: S. J. Sciutto (sciutto@fisica.unlp.edu.ar)
$^{(a)}$ Fellow of CONICET, Argentina.

[1] **AIRES** is an acronym for **AIR**-shower **E**xtended **S**imulations.

MAIN CHARACTERISTICS OF AIRES	
Propagated particles	Gammas. Leptons: $e^{\pm}$, $\mu^{\pm}$. Mesons: π^0, $\pi^{\pm}$; η, $K^0_{L,S}$, $K^{\pm}$. Baryons: p, $\bar{p}$, n, $\bar{n}$, Λ. Nuclei up to $Z = 56$. Neutrinos are generated (in decays) and accounted for their number and energy, but not propagated.
Primary particles	All propagated particles can be injected as primary particles. Multiple and/or "exotic" primaries can be injected using the *special primary* feature (see text).
Primary energy range	From 800 MeV to 1 ZeV (10^{21} eV).
Geometry and environment	Incidence angles from vertical to horizontal showers. The Earth's curvature is taken into account for all inclinations. Realistic atmosphere (Linsley model). Geomagnetic deflections: The geomagnetic field can be calculated using the IGRF model (Sciutto, 1999).
Propagation (general)	Medium energy losses (ionization). Scattering of all charged particles including corrections for finite nuclear size. Geomagnetic deflections.
Propagation: *Electrons and gammas*	Photoelectric and Compton effects. Bremsstrahlung and e^+e^- pair production. Emission of knock-on electrons. Positron annihilation. LPM effect, and dielectric suppression. Photonuclear reactions.
Propagation: *Muons*	Bremsstrahlung and muonic pair production. Emission of knock-on electrons. Decay.
Propagation: *Hadrons and nuclei*	Hadronic collisions using the EHSA (low energy) and QGSJET or SIBYLL (high energy). Hadronic cross sections are evaluated from fits to experimental data (low energy), or to QGSJET or SIBYLL predictions (high energy). Emission of knock-on electrons. Decay of unstable hadrons.
Statistical sampling	Particles are sampled by means of the Hillas thinning algorithm (Hillas, 1981), extended to allow control of maximum weights.
Main observables	Longitudinal development of all particles recorded in up to 510 observing levels. Energy deposited in the atmosphere. Lateral, energy and time distributions at ground level. Detailed list of particles reaching ground, and/or crossing predetermined observing levels.

Table 1. Main characteristics of the AIRES air shower simulation system.

ers measured at the Haverah Park experiment (Ave et. al., 2000).

In all the studies performed using AIRES, the results obtained present a good agreement with experimental data or simulated data coming from other sources, in particular, a recent comparative study of the AIRES and CORSIKA programs (Heck et. al., 2001) shows that the output from both codes are in excellent agreement.

The aim of this paper is to describe the relevant characteristics of the AIRES program, stressing on the most recent developments, and discuss briefly the strategy for future developments.

2 Characteristics of AIRES

The AIRES simulation system provides a comfortable environment for performing realistic simulations taking advantage of present day computer technology.

Table 1 summarizes the main characteristics of the particle propagating engine of AIRES.

The set of particles that are fully propagated by AIRES include the most commonly observed ones, together with other less numerous but capable of producing indirectly a non negligible impact on the final shower observables. All these particles can be injected as shower primaries. It is also possible to initiate showers produced by "special" primaries. This

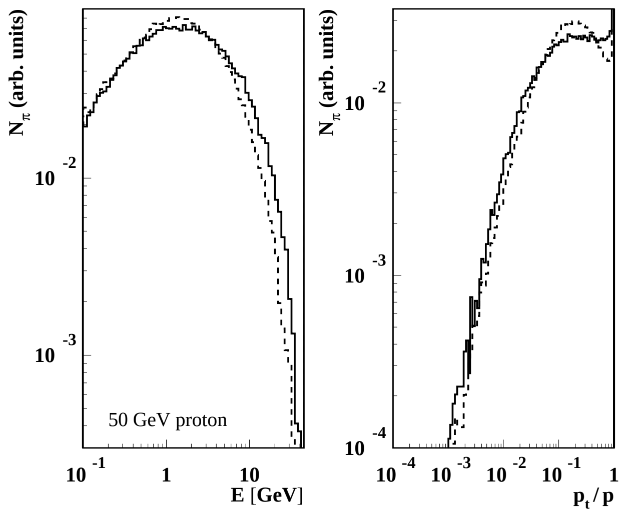


Fig. 1. Energy and transverse momentum distribution of secondaries generated by the extended Hillas algorithm (solid lines) and QGSJET (dashed lines) for collisions generated by 50 GeV protons.

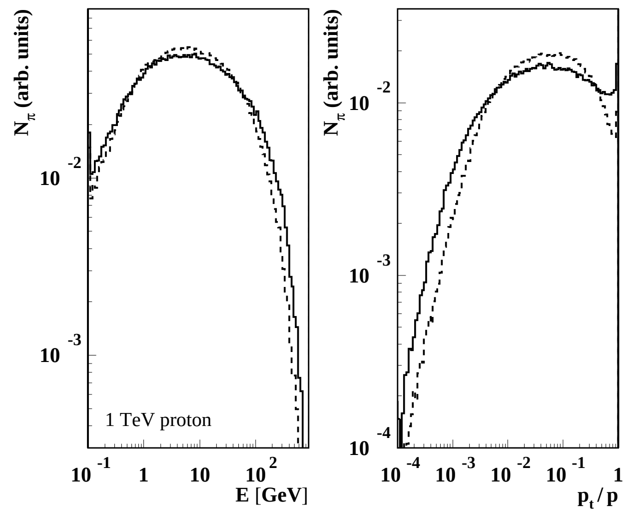


Fig. 2. Same as figure 1, but for collisions generated by 1 TeV protons.

useful feature of AIRES, explained in detail elsewhere (Sciutto, 1999) allows to dynamically call a user-defined module that generates the primary (or primaries) that starts the shower, thus extending the set of primary particles beyond the standard ones that are recognized by the propagating engine.

The interactions indicated in table 1 represent, for the case of air showers, the most important ones from the probabilistic point of view. Particle decays and electromagnetic interactions are simulated using built-in procedures that have been developed on the basis of tested and commonly accepted theoretical formulations. In the particular cases of the LPM effect (Cillis et. al., 1999) and the muon bremsstrahlung (Cillis and Sciutto, 2001), the development of such procedures has included exhaustive studies of the underlying physics. Additionally, we have recently finished a review of all the electromagnetic procedures implemented in AIRES, including the scattering algorithms. After this review, a series of minor changes were implemented to improve the accuracy and performance of the program.

However, our knowledge of the hadronic interactions is by far more incomplete than in the case of the electromagnetic ones. To process such interactions, it is necessary to rely on a given model, that is always based on phenomenology. Additionally, in an air shower, the energy spectrum of the hadrons undergoing inelastic collisions spans regions where there are no experimental data available, where the only alternative is to use the extrapolations provided by the available models.

In AIRES the hadronic collisions are processed by means of two models, depending on the energy of the projectile: For collisions with energy less than ≈ 100 GeV, an extension of the Hillas Splitting Algorithm (EHSA) (Hillas, 1981) is used, while for higher energies it is possible to select between QGSJET (Kalmykov et. al., 1997) and SIBYLL (Fletcher et. al., 1994).

In a previous work (Anchordoqui et. al., 1999) we made a comparative study of QGSJET and SIBYLL at the highest primary energy. More recently, and related with a comparative study AIRES-CORSIKA (Heck et. al., 2001), we analyzed the characteristics of the EHSA. In the following section we summarize some results of this study.

3 The low energy hadronic model

At energies below ≈ 100 GeV the high-energy models start to get problems, since particle production is constrained by the small amount of energy available, and a low energy model is necessary to process such interactions.

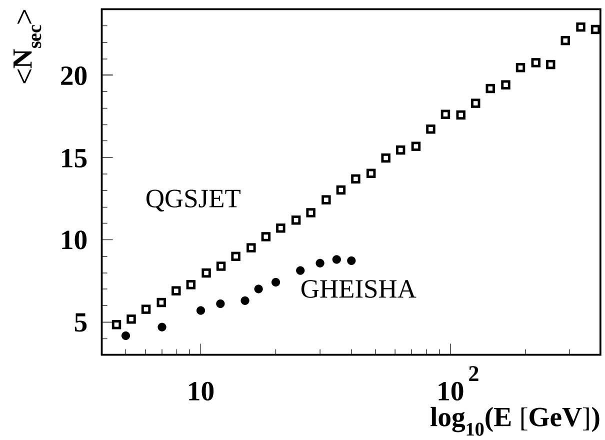
The low-energy model is of great importance, since all signals measured in an EAS experiment are produced by low-energy particles that come from low-energy interactions. Especially particle ratios and energies can be altered by those interactions.

As mentioned, AIRES uses the EHSA in which the initial energy is split at random into smaller and smaller portions. There are two free parameters, one regulates the mean energy fraction at which the splitting occurs and the other controls the number of subsequent splittings that are applied. Finally the energy portions are attributed to pions and nucleons. The EHSA can be easily configured to approximately emulate the multiplicities and energy distributions of other models. Cross-sections, transverse momenta distributions and composition of secondaries need to be inserted from outside[2].

Despite its simplicity, the EHSA can emulate with acceptable quality the main characteristics of the secondaries produced by other, more involved, models.

To illustrate this point we show here some results obtained from a comparison between QGSJET and the EHSA. In fig-

[2]The low energy cross sections can easily be obtained from fits to experimental data.



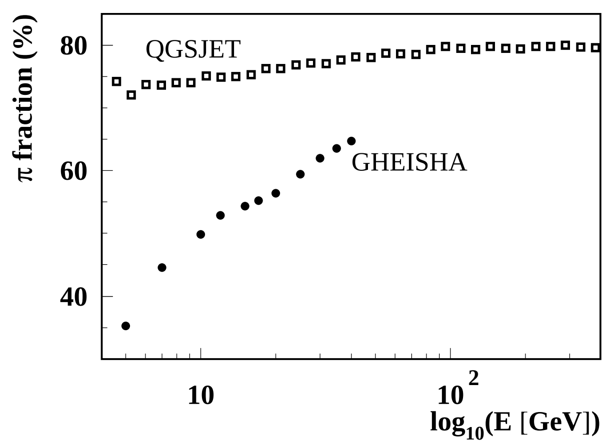


Fig. 3. Average number of secondaries (top) and fraction of pions (bottom) corresponding to inelastic collisions initiated by protons and processed using GHEISHA and QGSJET.

ures 1 and 2 the energy and transverse momentum distribution of secondary pions are displayed for the cases of 50 GeV and 1 TeV proton primaries, respectively. The solid (dashed) lines correspond to the EHSA (QGSJET). The agreement between distributions is acceptable, and this also applies to other observables and intermediate energies (not displayed here).

The parameters of the EHSA can be also easily adjusted to match the distributions coming from other models, including the ones designed to work at low energies like the well-known GHEISHA model (Fesefeldt, 1985). It is relevant to mention that at the transition energy (≈ 100 GeV) the predictions of GHEISHA and QGSJET do not agree completely, as it can clearly be seen from figure 3, where the total number of secondaries and fraction of pions, as measured from proton initiated collisions, are plotted versus the primary energy. Both plots show an evident discontinuity at the transition energy that in this case was set to 50 GeV.

We have taken profit of the flexibility of the EHSA to simulate the behavior of any of the two models to perform a survey of the influence of the low energy hadronic model on shower observables. From this study, we have found that there is a moderate dependence of some non-electromagnetic shower observables like the lateral distribution of muons, that present variations of up to 40 % at large distances to the core, that are clearly dependent on the settings of the low energy hadronic model. A more detailed study on this subject is in progress and will be reported elsewhere.

4 Final remarks

We have presented some of the main features of the AIRES system for air shower simulations, stressing on the recent developments than can be summarized as follows:

– All the electromagnetic shower algorithms have been checked.

– Complete treatment of muon radiative processes.

– Revised extended Hillas Splitting algorithms, tuned to match data coming from more involved models like GHEISHA and QGSJET.

– Experimental cross sections at low energies.

– Other minor changes.

We are presently working on the release of a new public version of AIRES that will contain all the reported features. The current status of the AIRES system can always be checked at the AIRES Web page:
`www.fisica.unlp.edu.ar/auger/aires`.

Acknowledgments

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